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## Technical Note

## A multifunctional device to simulate oral ageing: the “Rub&amp;Roll”

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## ABSTRACT

This article describes an in vitro fatigue and/or wear simulator enabling controlled application of force, speed, type of liquids and duration, to mimic challenges representative for the human oral environment.

The device consists of a container in which a cylinder with specimen holder is placed which drives another cylinder (rod). The rod rotates in an opposite direction to the rotation of the stirring motor, rolling over the specimens mounted in the cylinder. When the rod contacts the specimen a force is applied to mimic processes in the oral environment. The design, working and construction principles of a new device, the Rub&Roll, and some of the possible applications are described. Four different application examples are presented: occlusal wear in an low acidic abrasive slurry; combined erosive and abrasive wear of enamel exposed to apple juice or apple pulp; the wear of sealant material in natural teeth in an abrasive slurry; and the influence of mechanical loading cycles on micro tensile bond strength of an adhesive system to dentin. Application of the “Rub & Roll” device showed results which are clinically relevant, reproducible and in accordance with existing literature. **Conclusions:** The Rub&Roll enables controlled application of chemical and mechanical loading, allowing variation of force, sliding distance, velocity, number of cycles, and frequency, and a combination with erosive and abrasive challenges representative of those in the oral environment.

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## 1. Introduction

The oral human cavity is a complex environment where teeth, restorations and dental appliances are subjected to mechanical

(tooth-tooth or tooth-foreign object contact), chemical (body fluids and dietary products) and thermal challenges. These challenges lead to ageing, wear and failure due to fatigue. Wear factors are classified in various ways (Mair, 1992) and the dental

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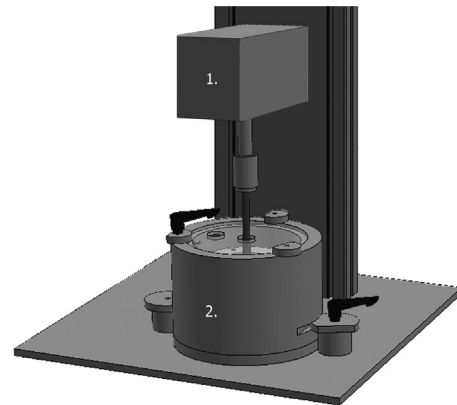
nomenclature, e.g., erosion and attrition, is sometimes different from that used in other fields of science like for example in geophysics. Tooth wear is generally regarded as the result of an interaction of several fundamental processes. In the behavior of intra-oral structures fatigue plays an important role. Fatigue wear occurs as a result of the formation and propagation of subsurface micro cracks when two surfaces move under dynamic load. A recent overview on the performance of dental composites stresses the importance of a resistance to fatigue for these materials (Ferracane, 2013). Composites that were subjected to dynamic mechanical loading prior to fracture testing demonstrated a reduction 45 to 62% of the static loading values (Lohbauer et al., 2006). Simulated oral aging is also considered to be essential in evaluating long-term adhesive bonding to dentin (Skovron et al., 2010). Subjecting materials to a regime of fatigue / aging is considered to make a test more predictive for their clinical behavior.

In 2006 a special issue of Dental Materials focusing on wear in all its facets was published. Lambrechts and colleagues discussed available wear testing devices and distinguished tooth brushing machines and two- and three-body wear machines (Lambrechts et al., 2006a, 2006b). According to the authors, the ideal wear machine perfectly mimicking the oral environment does not exist. Each of the machines has advantages and disadvantages, and limitations. Heintze compared in vitro and in vivo wear data and concluded that a strong correlation is impossible to obtain due to differences in patient-related factors (Heintze, 2006). The current available wear and fatigue machines make use of complex technology, are expensive and require special technical skills to let these devices perform well. Also, they often concentrate on a single type of challenge. This article describes a new in vitro fatigue and/or wear (aging) simulator that allows separate or simultaneous mechanical and chemical loading experiments, requires little technical support, is inexpensive and can be used to load a high number of specimens of natural teeth or restorative materials per experiment.

## 2. Material and methods

### 2.1. Design

The Rub&Roll consists of a container in which a cylinder is placed that is driven by a stirring motor (Fig. 1). In the cylinder up to at least 16 specimens can be mounted. Between the cylinder and the inner wall of the container there is a space of 14 mm in which one or more rod(s) are placed (Fig. 2). The rod is a RVS core in a PVC hose and is held between the inside of the container and the cylinder. When the stirring motor (cylinder) starts rotating, the rod rotates in an opposite direction to the rotation of the stirring motor, rolling over the specimens mounted in the cylinder. When the rod contacts the specimen a force is applied. Using shims, the top surface of the specimen can be positioned to protrude a predetermined distance from the surface of the cylinder. In that way forces up to 75 N can be generated on the specimen. The stirring motor can be set at different speeds to simulate the speed of mastication. In the container different kinds of liquids and abrasive slurries can be applied during the testing procedure, allowing a controlled mechanical and chemical loading.



**Fig. 1 – Schematic presentation of the Rub&Roll and its main components: 1) stirring motor, 2) container. The cylinder is attached to the stirring motor and placed in the container.**

### 2.2. Construction and working principle

The cylinder is attached to the stirring motor and fits with the aid of a locator pin exactly in the center of the container. When the cylinder starts moving clockwise it activates the rod that will move counter clockwise. As a consequence the rod will pass a different distance along the edge of the container than the cylinder (Fig. 2). By using the measurements of cylinder, container and rod, respectively, several parameters can be calculated, such as rod displacement (Table 1).

In a single rotation the rod moves 44 mm along the container, the angular rotation 0.56 rad. The displacement at the cylinder side can be determined by multiplying the cylinder radius by the angular rotation: 36.2 mm. The total displacement of the cylinder required to produce one rotation of the rod is  $36.2 + 44 = 80.2$  mm. This means that the rod will rotate around the cylinder  $408 / 80.2 = 5.1$  times (Fig. 3).

From this measure we can calculate the “delay” of the rod compared to the cylinder:  $408 / (5.09 \times 44) = 1.8$ . The rod will return to the start position after 1.8 rotations of the cylinder having turned 5.1 times around its own axis.

A maximum of 16 samples can currently be mounted simultaneously in the cylinder. All types of sample can be mounted, such as embedded flat enamel or dentin, or natural shaped complete molars or teeth with or without root. Also samples made of dental restorative materials can be tested. Samples are embedded in PMMA (Autoplast, Candulor, Wangen, Swiss) to fit in the sample spaces with their top flush with the cylinder surface. By using a shim, the sample can be made to protrude at a fixed height from the cylinder. The shim can be made from rubber to mimic resilience of the periodontal membrane movement and efficiently reduces the effect of contact force variation (Rues et al., 2011).

### 2.3. Configurable settings

#### 2.3.1. Rod

For the rod a standardized shape and size (diameter of 14 mm and a length of 85 mm) should be used. In order to ensure that the rod can rotate around the cylinder a flexible PVC coating is necessary. For simulation of the human mastication, according to Dejak et al. (2003) who did finite elements

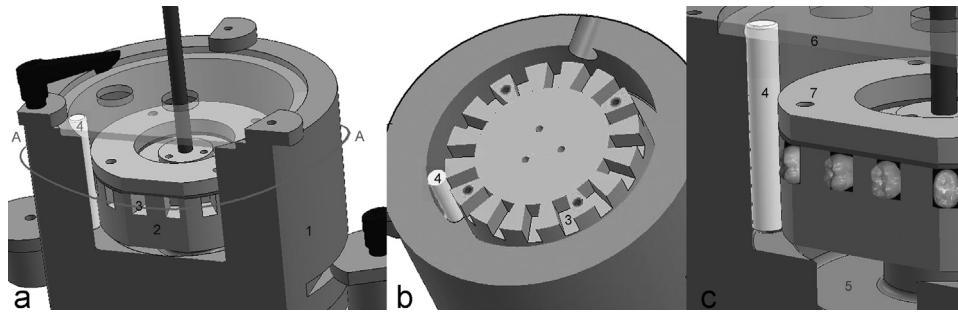


Fig. 2 – Inside view of the Rub&Roll with a) sliced front view b) section view AA c) thumbnail of sample mounted cylinder and rod. 1) container; 2) cylinder; 3) sample mounting space; 4) rod; 5) recess for debris and liquid/slurry outlet; 6) cover; 7) cylinder lid.

Table 1 – Rub&Roll dimensions and calculations for rod rotation and relative movement and speed at a setting of the cylinder rotation at 1 rpm.

	rotation speed rpm	Ø diameter mm	perimeter mm	S distance mm/min	Φ angular rotation rad	ω angular speed rad/s	ν peripheral speed mm/s	tooth contact chewing velocity mm/s
cylinder	1	130	408	408	6,3	0,1	6,8	
rod	5,1	14	44	224	31,7	0,5	3,7	3,1
container delay	1,8	158	496			3,1		

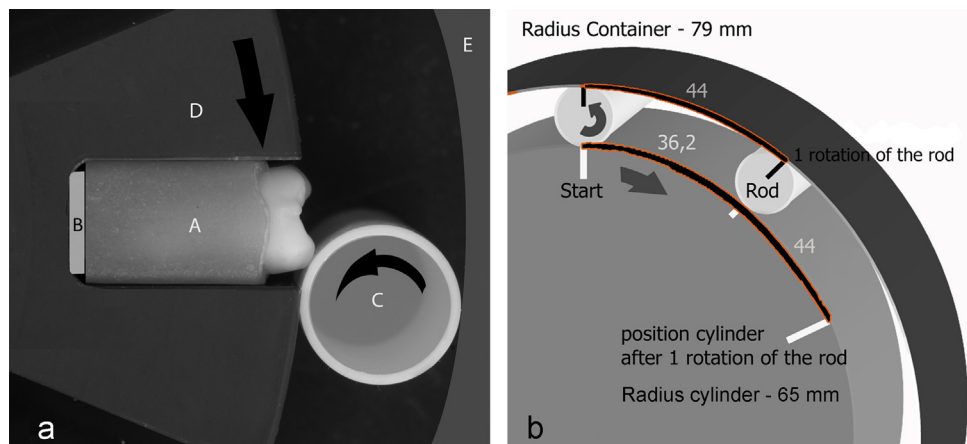


Fig. 3 – a) View on the inside of the container (E). The cylinder (D) containing the specimen (A) a molar embedded in acrylic resin supported by a shim (B). The rod (C) contacting the specimen and the outside of the container. b) Schematic view of the working principle of the Rub&Roll. The arrows indicate the directions of rotation of the cylinder and the rod.

analysis of stresses in molars during clenching and mastication, it is important to get a similar distribution of the forces in the mouth with different materials with low and high elastic moduli, therefore flexible or less flexible materials for the coating can be used. In this setup a PVC tube (Hardness 73 Shore A) with an outer diameter of 14 mm and inner diameter 10 mm was used with an insert of a stainless steel 316 (Hardness 130–150 HB) rod with a diameter of 9 mm.

### 2.3.2. Loading force

During chewing food will be crushed between the occluding teeth. The reaction force will vary, as the food bolus is more or less deformable. According to Míoche and Peyron (1995) the average masticatory forces in elastic, plastic and brittle

products are 30 N, 50 N and 70 N, respectively, with common food products being considered plastic. Chewing forces varying from 20 to 120 N are reported in the literature (Schindler et al., 1998). In the Rub&Roll the force can be varied using shims placed underneath the samples. The top surface of the specimens can thus be positioned to protrude a predetermined distance from the surface of the cylinder.

To measure the loads exerted on the specimens a single-point load cell (Scale components, model LOC SE, Celtron, Proweigh, Auckland, New Zealand, 1000 N accuracy  $\pm 0.03\%$ ) was attached to the outside of the container with a measuring piston extending through a hole in the container and protruding from the inside of the container. The force exerted by the rod on the piston was measured with a controller

SD2102 and operating software of Syrinx (Syrinx Industrial Electronics, Zwaag, The Netherlands). The resulting loads ranged from 0 to 90 N with a shim height (sample protrusion from cylinder) ranging from 0.3 to 2.75 mm (Fig. 4). The maximum load that could be applied without compromising the proper functioning of the apparatus was observed to be about 2 mm protrusion (75 N)

### 2.3.3. Chewing rate and lateral velocity

The rotation speed of the cylinder can be changed with the driving motor. Doubling the speed of the cylinder results in a doubling of contact moments (“chewing rate”).

A lateral movement is integrated into the wear simulation: the antagonist is moving over a surface while maintaining smooth continuous contact (Fig. 5). The speed of this movement is called lateral velocity (sliding speed). During the displacement of the rod by rotation of the cylinder the load is measured by a single-point load cell at different places of a tooth cusp (Fig. 5b). The shape of the cusp provides a comparable shape of the loading force profile although the contact radius of the rod is greater than for a natural opposing teeth.

From the displacement of the rod by one rotation of the cylinder we can calculate successively angular rotation (distance/radius) in radials, angular speed, and the peripheral

speed in mm/sec. The lateral velocity in this setup is therefore the peripheral speed of the cylinder minus the speed of the rod ( $6.8-3.7=3.1$  mm/s) (Table 1).

Fracturing of the food bolus during chewing takes place during the closing phase of the chewing motion, and depends on the mechanical properties of the food. For tough food the compression will be slower than for soft food (Koolstra, 2002). In literature a varying lateral velocity speeds can be found: from 65 mm/s (Anderson et al., 2002) to 2.5 mm/s (Lambrechts et al., 2006a). Also difference in lateral speed was reported between men and women: 42.5 and 28.9 mm/s, respectively (Lepley et al., 2011). In this set-up chewing velocities can be chosen from about 3 to 129 mm/s (Table 2.) In literature varying tooth contact time are found: 0.4–0.6 s (Heintze, 2006) and 0.12 s (Xu et al. 2008). At a contact area of 3 mm and rotations speeds of 1 to 15 rpm, the sample contact time covers this clinical range.

### 2.3.4. Number of cycles

The number of cycles is determined by rotation speed and total run time. One year of clinical functioning was reported to be simulated by 240000 chewing cycles with a load of 50 N (Heintze et al., 2012). This would mean a Rub&Roll run time of about 15 days at a rotation speed of 20 rpm. Inserting an extra rod in the set-up will double the loading frequency, however, 2 rods appears to be the maximum for proper functioning.

### 2.3.5. Liquids (erosive/abrasive)

During simulation of mastication with the “Rub&Roll” various types of liquids, slurries and foodstuffs can be added to the cylinder changing the erosive and/or abrasive properties as required.

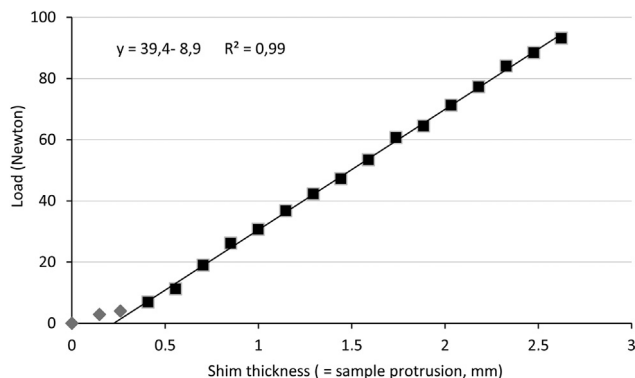


Fig. 4 – Loads exerted on the specimens by the rod, as a function of increasing sample protrusion (= shim thickness).

## 3. Examples of experiments performed with the Rub&Roll

### 3.1. Example 1

The effect of loading a natural occlusal surface in an erosive and abrasive slurry.

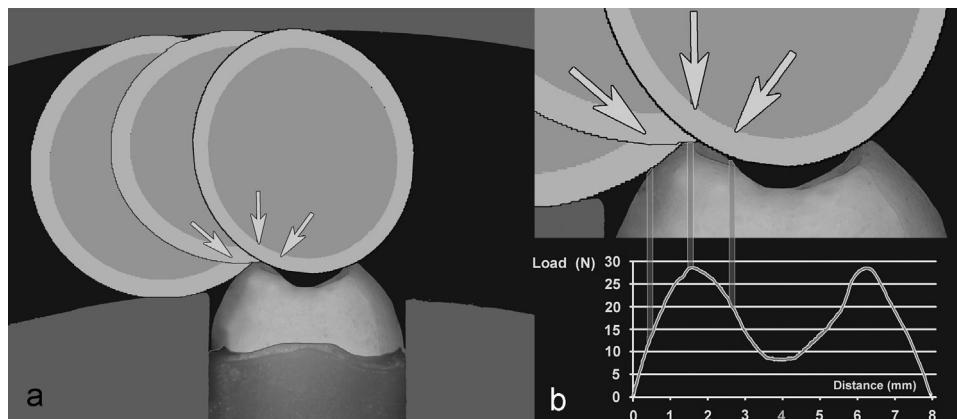


Fig. 5 – a) Direction of the load on the sample during rotation of the cylinder. b) The load applied to the cusp during rotation of the cylinder.



### 3.1.1. Rub&Roll settings

The speed of the stirring motor was fixed at 20 rpm, at 0.2 Hz. Loading consisted of 500,000 cycles and the force applied was 30 N. The medium used was the ACTA wear abrasive slurry, at room temperature (de Gee and Pallav, 1994), with an adjusted pH of 5.3.

Sixteen teeth were obtained from a selection of third molars with sound occlusal surfaces, and cleaned of gross debris. The occlusal surfaces were scanned with a non contact surface profilometer (Proscan 2100, Scantron Ltd, Taunton, UK) to evaluate enamel material loss in shape, grade and location.

The function of the Rub&Roll proved to be consistent and resulted in a typical wear pattern of smooth bordered wear facets on the loaded cusps (Fig. 6). This pattern is very similar to the clinical presentation of early erosive wear (Kahn and Young, 2011). The relationship between attrition, erosion and abrasion, which will create a worn dentition, can be properly investigated by changing the medium, forces and time in the Rub&Roll

### 3.2. Example 2

Wear of dental enamel exposed to erosive only or erosive and abrasive medium.

#### 3.2.1. Rub&Roll settings

The speed of the stirring motor was fixed at 20 rpm, at 0.2 Hz. Four loading periods of 22,5 min (225 chewing cycles) were used, adding up to 90 min (900 chewing cycles), the force

applied was 30 N. The medium used was 500 ml apple juice or 500 ml apple pulp in 200 ml apple juice at room temperature.

Bovine enamel samples which were polished flat with sandpaper grit 220 and cut with a diamond wafering blade to dimensions of approximately  $5 \times 8$  mm and subsequently embedded in polymethylmetacrylate (PMMA). Both end sides of the enamel sample were covered by tape to provide 2 reference areas to measure the wear. To simulate chewing, which results in production of saliva and the buffering of the acid, the four loading periods of the experiment were performed at increasing (controlled) pH-values, for both groups at the same level.

Enamel samples were scanned by a non contact profilometer (Proscan 2100) and the depth of the erosive wear was calculated on a selected area of  $4 \times 6$  mm. The wear expressed in enamel loss for apple juice and apple pulp was  $7.5 \pm 2.7 \mu\text{m}$  and  $13 \pm 1.7 \mu\text{m}$ , respectively. The addition of apple pulp significantly ( $p < 0.001$ , t-test) doubled the enamel wear. The experiment was performed in two runs, with less than  $0.5 \mu\text{m}$  difference between the run results ( $p = 0.7$ , t-test), showing good reproducibility.

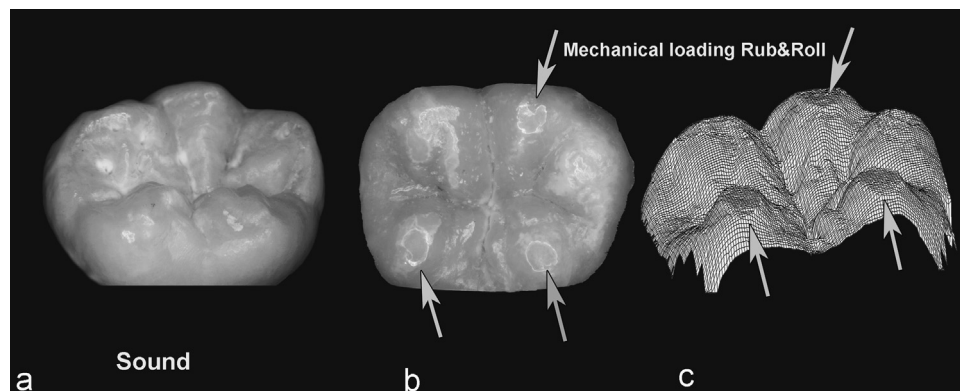
It clearly demonstrates that not only pH of a food but also its texture and abrasiveness influences the wear of enamel. The Rub&Roll allows for the combined testing of these factors.

### 3.3. Example 3

Wear and retention of fissure sealant material placed in human molars after abrasive / mechanical loading.

**Table 2 – Lateral velocity, contact time, number of cycles after 1 day, and loading frequency for different settings of cylinder rotation speed. The contact time is calculated for a contact area of 3 mm.**

rotation speed rpm	tooth contact chewing velocity mm/s	tooth contact (3mm) cycle duration s	tooth contact chewing- loading cycle 1day	tooth contact frequency Hz
1	3,1	0,98	790	0,01
5	15,4	0,20	3950	0,05
10	30,7	0,10	7900	0,09
15	46,1	0,07	11850	0,14
20	61,5	0,05	15800	0,18
25	76,8	0,04	19750	0,23
30	92,2	0,03	23700	0,27
35	107,6	0,03	27650	0,32
40	122,9	0,02	31600	0,37



**Fig. 6 – Digital image of occlusal tooth surface a) sound; b) after loading in an erosive/abrasive slurry during 500,000 cycles; c) profilometric image after mechanical loading. The arrows indicate the resulting occlusal wear areas.**

### 3.3.1. Rub&roll settings

The speed of the stirring motor was fixed at 20 rpm, at 0.2 Hz. Loading consisted of 120,000 chewing cycles. The force applied was 30 N. The medium used was the ACTA wear abrasive slurry pH=7.2, at room temperature (de Gee and Pallav, 1994).

Sixteen teeth were obtained from a selection of third molars with sound occlusal surfaces and deep pits and fissures, and cleaned of gross debris. The samples were sealed with glass-ionomer: Ketac Molar Easymix1 (3MESPE, Seefeld, Germany) according to the manufacturer's instructions. The occlusal surfaces were scanned with a non contact surface profilometer (Proscan 2100, Scantron Ltd, Taunton, UK) before and after loading, to evaluate sealant material height loss. The difference in height of the sealant was measured on nine different places and averaged. The samples also were also digitally recorded before and after loading and manipulated with image analysis software, to evaluate sealant retention loss.

A mean sealant height loss of  $55.9 \pm 15.7 \mu\text{m}$  was observed, and the digital photographs also showed a loss of surface coverage or retention (Fig. 7).

### 3.4. Example 4

The effect of mechanical loading on micro tensile bond strength ( $\mu\text{TBS}$ ) of an adhesive system to dentin.

#### 3.4.1. Rub&roll settings

The speed of the stirring motor was fixed at 20 rpm, at 0.2 Hz. Aging period of 250,000 cycles and the force applied was 30 N.

The storage-medium was distilled water at room temperature.

Twenty extracted sound human third molars were selected, cleaned and stored in water with chloramine, at 5 °C. After removal of occlusal enamel flat dentine surfaces were exposed. The teeth were embedded in acrylic resin resulting in samples with the follow specific dimensions: 16 mm in height  $\times$  14 mm width  $\times$  10 mm length. Dentin surface was polished with the 800-grit silicon carbide paper to create a uniform smear layer. The adhesive system used was a two-bottle self-etching adhesive system Clearfil™ SE Bond – CSE- (Kuraray, Japan), which was applied according to the manufacturer's instructions. A hybrid composite (Clearfil™ AP-X, Kuraray, Japan) was bonded to the surface in a uniform layer of 4 mm in height. The samples were randomly assigned to the following aging conditions: Control (no loading): 24 h distilled water, at room temperature; and mechanical loading in the Rub&Roll.

After the aging conditions, the samples were sectioned into stick-shaped beams with an approximate cross-sectional area of  $1 \text{ mm}^2$ , using a low speed diamond saw under continual water cooling, followed by a trimming method described by Shono et al. (1999). This resulted in 15 to 20 beams for each sample. Each beam was measured prior to testing with a digital caliper (Mitutoyo America Corporation, USA) in order to calculate the adhesive surface area. The samples were tested for micro-tensile bond strength ( $\mu\text{TBS}$ ) by attaching them with superglue adhesive (Cyanoacrylate Rite-Lok, 3 M, UK) to a movable jig in a Universal Testing Machine (Materials Testing Machine LS1, Lloyd Materials Testing, Hampshire, UK, load range 1 kN). The beams were stressed up to failure at a crosshead speed of 1 mm/min.

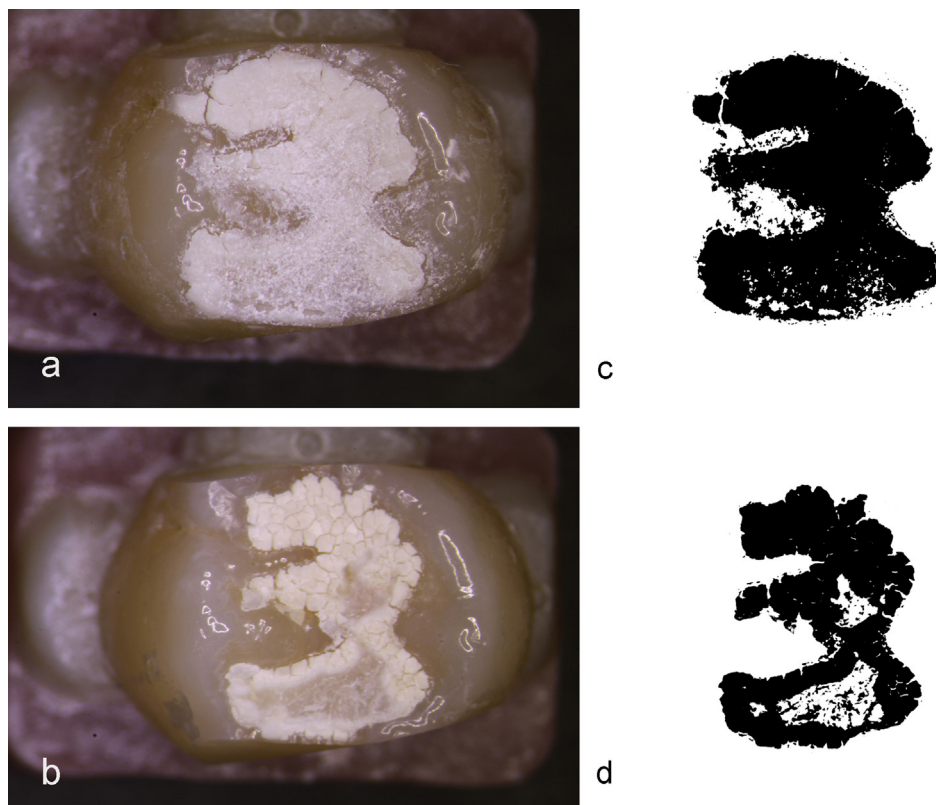


Fig. 7 – Digital photograph of sealed tooth before (a) and after (b) loading in the Rub&Roll. Same images after manipulation, showing only the sealant area before (c) and after (d) loading.

The bond strength ( $\sigma$ ) in MPa was obtained with the formula  $\sigma = F/A$ , where  $F$  = load for sample failure (N) and  $A$  = bonded area ( $\text{mm}^2$ ).

The results of the experiment, with the mechanically loaded group ( $\mu\text{TBS } 21,9 \pm 15,6 \text{ MPa}$ ) showing about 30% loss of bond strength as compared to the water stored group ( $\mu\text{TBS } 32,4 \pm 14,2 \text{ MPa}$ ). The difference was statistically significant ( $p = 0.035$ , t-test).

These results are in agreement with the literature, where mechanical loading has been shown to affect adhesive bonding (Lodovici et al., 2009; Skovron et al., 2010; Mutluay et al., 2013). Relatively low loads and high cycle numbers are needed to simulate clinical performance (Heintze et al., 2012; Lodovici et al., 2009).

#### 4. Discussion

In the literature several wear testing devices are described. A drawback of most of these devices is the fact that they are not simple to use, are technical demanding and expensive. Moreover, they usually only simulate a single aspect of normal clinical challenges, e.g., chewing loads, or abrasive loads, but not a combination. Until now, there is no device available that really can simulate the oral environment in all its aspects. Also the lack of international acceptance of in vitro methods for evaluating wear behavior of dental materials makes it difficult to compare in vitro wear data (Lee et al., 2012).

The examples presented showed different promising applications of the new device. We have shown initial evidence for validity, in producing clinically relevant wear, comparability of results to those obtained in the literature, and reproducibility in repeated experiments, but much more research is needed to demonstrate the validity of the device in mimicking fatigue and wear processes in the human oral environment.

The Rub&Roll is a machine that is not technically demanding, is robust and can apply loads to 16 specimens that are simultaneously subjected to different kinds of liquids or slurries. In function both the direction as well as the magnitude of the load will vary which is comparable to normal chewing (Xu et al. 2008). Most simulators induce a single occlusal contact with a given force and a straight sliding movement instead of mimicking a real chewing movement.

According to Heintze et al. 2006 oral wear simulators should have the following system specifications and tolerances:

Ability to deliver dynamic forces between 20–120 N.

Controlled forces between 5 and 75 N can be performed in the Rub&Roll

Loading profile resembles chewing food: half, sharp sine wave as force profile.

Together with the speed of the motor and the shape and material of the Rod the occlusal force and velocity can be influenced, mimicking the force profile of chewing cycles.

A distance between the contact areas of molars with vertical movement between 16 and 20 mm.

The distance between the cylinder and the container is 14 mm. There will be clearance since the cylinder will be moving while there is no obstacle at the surface of the tooth.

A contact time of on average 400–600 ms per chewing cycle

The contact time is adjustable from 1000 to 15 ms, assuming there is a contact area of 3 mm of the tooth and it can be adjusted by changing the speed of the stirring motor

An average sliding movement of 0.3 mm in the first molar towards the anterior and 0,18 mm towards the medial side.

A lateral movement is integrated in the Rub&Roll, which means that the antagonist is moving over a surface while maintaining smooth continuous contact, depending on the shape of the specimen and force adjustments. This rolling motion of the rod is not the same movement as occurs in the mouth but the movement of the rod is similar to the chewing movement in clinical circumstances. Slippage between the cylinder and the rod may take place by a lubricating effect of the medium and / or an increased pressure due to the structure of the medium and this will cause the frequency of tooth contacts to decrease. To monitor this, a sensor for measuring the number of rotations of the rod can be mounted.

Clearance: By adding medium to the device may wash away wear materials

After loading there is a continuously clearance during rotation in liquid (slurry).

As shown, the Rub&Roll appears to fulfill most of these requirements, while combining a variety of challenges making the testing of materials more predictive to the clinical situation. The examples support the versatility of the machine. In example 1 the Rub&Roll was used to for simple mechanical loading of composite adhesively bonded to dentine. The device promoted reduction of  $\mu\text{TBS}$  after 250,000 cycles. The mechanical loading may aid in predicting clinical effectivity while testing materials in vitro. In example 2 enamel samples were loaded in erosive / abrasive slurries of different composition. The abrasive wear caused by the fibers of the apple in an acidic environment, simulating the chewing sour fruit, is likely to play an important role in the erosive wear process. In example 3, wear and retention of a fissure sealant was tested in an abrasive slurry. The combined loading in the Rub&Roll, mimicking chewing of foods, resulted in wear rates of the sealant placed in anatomically shaped occlusal surfaces.

The full potential of the Rub&Roll still has to be explored. A few of the future possibilities, still under development, can be given. The rod can be modified to simulate different antagonists, so the specimen will come in contact with either PVC or other materials, e.g., dental porcelain or composite. Also it is possible to vary for instance shape and roughness. The medium could be thermally controlled to enable thermocycling. Simultaneous loading and thermocycling may be important factors in gingival micro leakage of dental restorations. Cyclically changing the medium would allow for de- and demineralization experiments, thereby extending the possibilities to caries simulation.

#### 5. Conclusions

The Rub&Roll is a newly developed machine for simulating oral challenges. Its advantages in the light of existing systems include:

Variable loading options: It allows for variable setting of chewing force, sliding distance, lateral velocity, number of cycles, frequency.

Flexibility in sample type and shape: The Rub&Roll can accommodate test samples in various shapes (natural formed teeth/ prepared teeth).

Variation in liquid medium: Different types of liquids and/or slurries can be used, allowing for chemical challenges.

Limitations of the machine are mainly

Lack of individual sample monitoring: The high number of samples that can be tested simultaneously, while allowing for better efficiency, makes it impossible to closely monitor each individual sample.

Limitation of exerted force: At the moment the maximum force is 75 N.

We conclude that the Rub&Roll is a promising device for studying aging and wear of teeth and dental materials under varying circumstances, which could assist in understanding and managing clinical wear (Mair et al., 1996)

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